Factors in the Behavior of Ground Water in a Ghyben-Herzberg System

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INTRODUCTION

THE HYDROSTATIC RELATIONSHIP between fresh ground water and sea water along coasts and in many islands has been recognized for about 60 years, since the work of Badon Ghyben (1889) and of Herzberg (1901). It has been studied in various parts of the world but perhaps nowhere are there more data concerning it than in Hawaii. In the course of the Pacific war the occurrence of ground water on many islands has been of crucial importance and the concept of a Ghyben-Herzberg lens has become widely circulated.

Rain falling on the surface of an ideally permeable circular island in the ocean is in part absorbed into the ground. This water percolates downward and accumulates at the surface of the salt water at sea level. The fresh water builds up to a height above sea level determined by its amount and by the permeability of the island rock, and also presses downward until it extends about 40 times as far below sea level as it does above sea level. The upper surface of such a ground-water body can be shown to be a domed one, and the lower surface is deeply curved because of the ratio of 1 to 40. The fresh-water body thus approximates the form of a double convex lens, with the circular edge coinciding with the circular coast (Fig. 1). This is the Ghyben-Herzberg lens, and the model on which the theory rests. In many places, owing to differences in rock structure, only a portion or sector of the lens will be developed, but the principle applies equally well.

The Ghyben-Herzberg balance is not by any means universal along ocean coasts and one may presume that it is well exemplified along only a small fraction of continental coasts. Otherwise it would probably be better known. Its somewhat limited occurrence is due to the requirement of rocks within a certain range of permeability, sufficient rainfall, and lack of specialized structure in the rocks. The rock structure must in the main be fairly homogeneous and be isotropically permeable if a well-characterized Ghyben-Herzberg system is to develop.

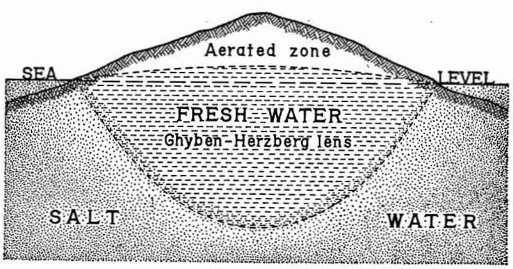

FIG. 1. Section through an ideal permeable island in the ocean, showing the form of the fresh-water body known as the Ghyben-Herzberg lens. Owing to scale limitations the bottom of the lens is shown only about 10 times as thick as the top part, instead of the 40-fold relation that occurs in nature.

In Hawaii, the principle of balance has become well known because of its remarkable development in the Honolulu–Pearl Harbor areas and in a few other localities on Oahu (Alexander, 1908; Andrews, 1909; Palmer, 1927: 17–20). It is not present or at least is scarcely demonstrable along about half of the windward coast because the rock is of low permeability and unsuitable structure. It is also much less developed on most of the other islands of Hawaii. Practical im-

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portance of the lens is great because in it a much greater thickness of fresh or near-fresh water is accumulated at sea level than would otherwise be the case. In fact the fresh water is perched on salt water. Because of the wide extent of such possible perching, these basal water bodies lying in Ghyben-Herzberg balance are the largest ground water resources of the region.

In rocks not favorable for developing such a lens, there may be springs of fresh water at sea level. These springs are mostly small and unimportant and are occasioned by the cutting of the sea against the land, by an action such as that which produces valley-side springs. In Hawaii the basal water which is in Ghyben-Herzberg balance may, or may not, be in part artesian. Where a cap rock exists, the thickness of the lens is increased by its retardation; but the cap rock is not essential. The development of hydrostatic balance occurs even where the lighter water of the lens is somewhat brackish. Such a system may be of true Ghyben-Herzberg form even where the land water carries a considerable fraction of sea water. But for practical use only the more perfect systems where the upper water has less salt than corresponds to about 1 to 2 per cent of sea water are of interest. Salinity of the Honolulu city supply corresponds to approximately 1/400 sea water.

Often water supply systems are planned where there is some indication of fresh land water at the coast. Here it is supposed that only drilling or tunneling may be needed to secure a potable supply. Often such excavation after prolonged test may show that despite some degree of Ghyben-Herzberg functioning the resulting developed water is too saline for the proposed use. Or, the water may grow progressively more saline and show that the hydrostatic system is not sufficiently stable to stand the disturbance of even a moderate draft of water. Engineers and others who have accepted the principle are naturally disappointed and in turn question it after such adverse tests. But in the writer's view it is not surprising that the fresh-water lens in certain areas is either lacking or fails to meet the extremely severe test of yielding potable water continuously. Rather, it continues as one of the natural wonders that such systems as that at Honolulu and a few other places have been developed in course of geological time, in such perfection and with such ability to withstand modification through artificial development of the water. These systems are the exceptions rather than the rule.

Observations in various parts of Hawaii and a growing knowledge of basal water conditions on other Pacific islands permit some broad generalizations concerning the conditions essential to an effective Ghyben-Herzberg system. An attempt is made in this paper to outline the requisite conditions.

In the course of compiling this discussion, the manuscript has been read and criticized by Charles V. Theis, Arthur M. Piper, L. H. Herschler, and Gordon A. Macdonald, each of whom has made valuable suggestions. The writer is indebted particularly to the latter, with whom he has had many most profitable discussions on this and related problems over a period of years.

OUTLINE OF FACTORS

In outlining the factors affecting salinity, attention is first drawn to the fact that the Ghyben-Herzberg lens consists of a lighter liquid, floating on a heavier liquid and miscible with it. If the two liquids were not miscible, they could maintain their separate character and their common boundary indefinitely even without being restrained in a permeable aquifer. However, as they are miscible, if the permeable aquifer were not present the two liquids would become mixed and diffused in a short time so that the lighter lens would be destroyed. On the other hand, if the rock at sea level is not permeable, there is no opportunity for a condition of hydraulic balance to become established. The fresh water cannot adjust itself to the salt water in relation to sea level and thus no Ghyben-Herzberg lens will be formed.

The first requisite is then a suitable degree of permeability. This must be small enough to prevent the general mixing which would destroy such a system and large enough to permit fresh water under the existing head differences to move against sea water. Only then can fresh water progressively displace salt water in forming a Ghyben-Herzberg lens. It will be seen presently that the permeability which proves effective is relative to other factors, and can be better discussed after these have been listed.

Next to suitable permeability is an infiltration of rainfall of sufficient amount and continuity to build and maintain a fresh basal ground-water body about a foot or more above sea level. According to the rainfall and recharge, there is built a surcharge above sea level adequate to discharge the average daily or annual amount to the periphery of the island. The maintenance of this surcharge causes the downward accumulation of fresh water until an approximate Ghyben-Herzberg lens is produced. The miscibility of the fresh and salt water tends to destroy the lens or the sharpness of its margin. The rate of addition of fresh water must be sufficient to overcome this tendency.

The third requirement is a sufficiently small fluctuation in both ground-water heads and in sea-water levels to minimize the effects of mixing and the spread of the zone of mixing through reversal of movement. Fluctuations in ground-water head are due to seasonal and other variations in rainfall and recharge. Chief changes in sea level that we need to consider are those due to tides. It seems fairly certain that small islands, which with tidal range of 2 feet show moderate stability of the Ghyben-Herzberg lens, if subjected to a 15- or 20-foot tidal range would show serious disturbances of the lens.

It is difficult to give any categorical specifications, but the best-known Ghyben-Herzberg water bodies in Hawaii do not have seasonal or annual fluctuations of water table exceeding perhaps one fifth of the total height of water table above sea level. It seems likely that any annual change such as half or two thirds of the mean value would tend to prevent growth of a lens from which any potable water could be taken. Both in their accomplishment and also in their effect on water quality, the amplitude of such fluctuations is obviously related not only to the infiltration changes but also to the permeability.

A fourth factor, and in some ways the most important of all, is that of comparative uniformity and regularity of permeability, and freedom from large and long openings crossing the boundary between fresh and salt water. Much of the effectiveness of the Ghyben-Herzberg mechanism depends on the maintaining of a fairly smooth and orderly boundary between the two liquids, as closely analogous as possible to the mathematically definable boundary between immiscible liquids. It is fairly evident that the actual condition is somewhat remote from this and, with fluctuating directions of movement, that existing large fissures or tubes must carry long filaments of one sort of water into the realm of the other, and vice versa. Such conditions seem to explain the observed vagaries in the composition of water from different wells in the same district and even at the same depth. Despite such irregular and fluctuating interpenetrations, a broad regularity of boundary is shown in the more stable Ghyben-Herzberg systems such as those of Oahu. Certainly if changing heads tend to move the salt–fresh boundary up and down alternately, any large openings which cross the boundary will be much more destructive in promoting interpenetration of one kind of water by the other than small openings. It appears clear that heterogeneous permeability will be more likely to produce an irregular and disorderly boundary than a homogeneous or regular permeability.

A fifth factor of importance is the effectiveness of a cap rock along the coast. Such a barrier not only promotes the building of higher heads of fresh water but indeed creates a condition somewhat akin to a U-tube so that at their two upper surfaces the fresh- and salt-water bodies are effectively separated. The first and most advanced intermixing of salt and fresh water would normally take place at the coastal margin. Here changing head differences would be exerted across the shortest distances between fresh ground water and free sea water. Evidently a barrier along the coast would have marked protective value. In the Honolulu area the thickness and width of the cap rock are such as to interpose a distance of several thousands of feet in most places between the water table and free sea water, and this barrier is of tremendous importance.

The factors mentioned above are, in summary: (1) suitable permeability, (2) adequate infiltration, (3) limited fluctuation, (4) regularity of permeability, (5) an effective cap rock. Some aspects of their interrelationships will now be discussed.

PERMEABILITY

It would be difficult to over-emphasize the importance of time in the inter-relationship of the several factors. The first factor, permeability, is of course a rate of discharge through a specified cross-section, and infiltration is expressed as an amount per unit of time and per unit of area. It is the lag in the dissipation of infiltrated water through permeable rocks which causes the initial accumulation of ground water and determines the ultimate head at which balance between gain and loss will be reached. In general, on islands of similar geometrical form, infiltration proceeds through areas that are proportional to the squares of linear dimensions, whereas for the same heads, the areas through which discharge to the sea takes place are proportional to perimeters, hence to the first powers of linear dimensions. Hence derives the tendency to build higher water tables on larger islands, thus restoring some degree of equality with this second dimension. It is also true that larger islands have longer radii and greater likelihood of continuous discharge even with discontinuous rainfall and infiltration.

Permeability that is too great (relative to infiltration and other factors) will result in a water table so low that no permanent pressure against salt water will be maintained and no permanent Ghyben-Herzberg lens will exist. On the other hand, if permeability is too low the amount of water infiltrated will be small, and the exerting of a systematic pressure against the sea water is less likely to be established. With the higher water tables due to less permeable rocks there is less likelihood that rocks of reasonably uniform permeability will extend to the depth below sea level requisite for a functional system. Moreover, even if balance exists, the lesser permeability precludes the detectable response by which we might recognize it. Thus on various less observable grounds the Ghyben-Herzberg condition vanishes also with reduced permeability.

It is possible, too, that in some islands the rock near sea level and slightly below at the coast is less permeable than the general mass below sea level and farther inland. Such difference within a favorable range of magnitudes would promote the Ghyben-Herzberg condition.

INFILTRATION

It is hardly practicable to suggest a numerical definition of adequate infiltration, but some limiting data may be offered. On some of the larger islands of Hawaii, where the discharge through the shore perimeter in some sections reaches values of 5, 10, or even 20 million gallons daily per shore-line mile, with other conditions favorable, Ghyben-Herzberg conditions are conspicuous and stable. These conditions imply some intake area with annual rainfall of 100 inches or more. In many other areas of Hawaii, on leeward coasts or on smaller islands, where rainfall is mostly under 50 inches and ground-water discharge is 1, ½, or 1/10 M.G.D. per shore-line mile, the Ghyben-Herzberg condition is either missing or non-demonstrable on the scale of practical water-supply operations. However, it should be remembered that under wartime or expeditionary conditions a vestigial fresh-water lens may be of great temporary value even though it may fail on continuous mechanized development.

The size of the island is important here; on an island 2 miles in diameter the discharged ground-water fraction required to equal 1.0 M.G.D. per shore-line mile is 42 inches over the area, whereas on one 10 miles in diameter 42 inches over the area will give 5 M.G.D. per shore-line mile. From experience in Hawaii the latter would quite likely have the Ghyben-Herzberg condition; the former very likely would not, unless the permeability or cap rock were especially favorable.

It may now be practicable to say that the required permeability assumed to be fairly homogeneous throughout the whole thickness is such as will require the water table to build up 2 to 10 feet or more and remain at nearly constant levels perennially. With lesser heads some degree of concentration of fresh water may be found but it is less likely to be stable against mechanized exploitation.

FLUCTUATION

The permissible annual fluctuation so far as we can estimate at present is somewhat less than one half of the mean water-table head, and in most cases less than one fourth of that head. No data are at hand, for any system of the magnitude of that of Honolulu, in which greater fractions of fluctuation are known. For systems with head of 5 feet or less it seems indicated that fluctuation from 2.5 to 7.5 feet of head would be fatal to useful Ghyben-Herzberg stability. No data are available to determine what ratio of short-term fluctuations might be tolerable, but naturally the tolerable limiting amplitude would be lower than for the longer term ones, and in the nature of the case they are materially less.

REGULARITY OF PERMEABILITY

By regularity of permeability we mean homogeneity of distribution and sizes of interconnected openings. A formation consisting of well-sorted sand or gravel would throughout its mass have regular permeability. A formation consisting of moderately permeable material but broken by large, irregularly spaced fissures or caverns would have irregular permeability. The adverse effect of irregular permeability would lie in introducing large and changeable irregularity of pattern in the three-dimensional network of surfaces of equal pressure and hence of lines of flow, of velocities, and of salinities. It is evident that in formations permeable enough to meet the Ghyben-Herzberg requirement, large irregularities will promote intermixing and tend to effacement of the zone of balance, which without frictional retardation can only be stable between immiscible liquids. In a sense, large openings of such length and direction as to lead across the zone of mixing are to be regarded as short circuits which would produce potential disturbance analogous to that in an electrical network. Moreover, the movement of saline water toward fresh, or vice versa, taking place during any phase would leave residues of great importance. It therefore appears that, increasingly, irregularity of permeability would tend strongly toward effacement of the salt-water–fresh-water contact on which the Ghyben-Herzberg lens depends, just as would increase of general permeability.

It appears that this variation in permeability, with some large openings going outside the favorable range of permeability, may be a very large factor in explaining the great differences in the Ghyben-Herzberg conditions on different coral limestone islands, or on different parts of the same island. Not only initial differences due to structure of the calcareous accumulation, but also fissures developed near sea level by the action of fresh water probably are important here. Such an interpretation has been suggested by the writer's observations in the Marianas during early stages of military operations there and has also been emphasized by others.[2]

CAP ROCK

It is not difficult to show why an effective cap rock is so very significant in permitting the growth of some of the larger Ghyben-Herzberg lenses. It is an essential part of that theory that in a steady condition of dynamic balance, with the thickness of the lens neither increasing nor decreasing, lines may be drawn from various points of the top of the lens (the water table) passing downward and outward in a wide curve to emerge in the ocean surface, along which hydrostatic pressures are in balance. If the position of the water table is changed by fluctuations of recharge or of loss, movement will tend to take place along these lines in accordance with the size of openings and length of path. It is evident that those paths

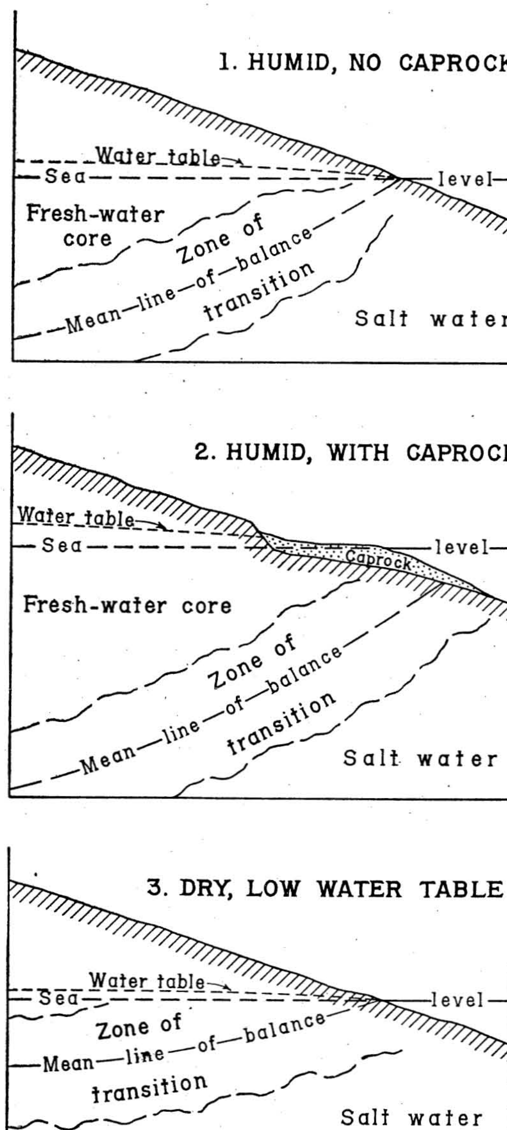

FIG. 2. Schematic sections through the margin of a Ghyben-Herzberg lens, under the three conditions indicated in the text. For convenience in drawing, the mean line of balance is based on a ratio of 10 : 1, rather than the true ratio of approximately 40 : 1.

[2] Piper, Arthur M. Letter dated December 5, 1946.

nearer to the shore line are much the shorter and that under fluctuating conditions of unbalance, water movement in larger openings across the zone of contact would take place here more rapidly than elsewhere (see Fig. 2). Along a shore unprotected by a cap rock, the thin edge of the Ghyben-Herzberg lens would be especially vulnerable to disturbance or destruction during marked fluctuations. There, particularly, the adverse effect of large fissures or other irregularity of permeability is certain to be great.

From these considerations, the value of a cap rock as a barrier between fresh and salt water is readily seen. As stated elsewhere, the interposition of the cap rock between fresh and salt water in effect completes the physical pattern of a U-tube. It tends to raise the head of basal water and to truncate and thicken its shore margin. This barrier has the result of eliminating the thin edge of the lens, with its dangerous sensitivity to plus and minus fluctuations. It should not be overlooked, also, that in most places the Ghyben-Herzberg condition is first recognized and is most useful in the shore zone where the water is most accessible and often most needed. It is possible that more complete and more extensive exploration will demonstrate the interior existence of Ghyben-Herzberg lenses in some islands where the condition is not well shown at the shore; such discoveries would confirm the contentions of this paper.

PARTS OF THE LENS

In the preceding sections, the five factors controlling the establishment and growth of the Ghyben-Herzberg lens have been discussed. Attention is now directed to the parts of the lens and to the nature of its lower boundary. It has been accepted that the lower surface of the lens is a zone of transition from fresh to salt water, and that since the two liquids are miscible the zone will have thickness. The perfect condition of a sharp boundary can only obtain with immiscible liquids. If the permeability is too great for the amount of infiltration, or if there is great irregularity of permeability, the mixing and mutual interpenetration of the two waters will be promoted and the zone of transition will be thickened. Such mixing may go so far that no part of the lens is free from salt contamination.

GROWTH OF DIFFUSION ZONE

Another effect, that of fluctuation or alternate movements of the zone of transition, may not be so readily discerned. With immiscible liquids and no matrix such as rock, the contact surface would move up or down according to relative pressures and with little or no deformation. However, in rock with miscible liquids, the migration of the zone downward into rock formerly filled with salt water would first involve driving out some of the salt water. But it would also result in assimilation of some of the salt water remaining longer in smaller openings. If such a process continued, the water composition at any one place would tend to approximate more and more that of the advancing water and retain less and less of the quality of the water originally displaced. However, there would commonly, after any short time, be some residue of the displaced water. If we assume that at any given time the local composition is a function of the compositions of the two waters and of the time during which Water A has moved into the realm of Water B, a process analogous to the exponential law of rinsing, some interesting consequences appear. If, for example, the two waters have an initially sharp boundary, and that boundary is moved under hydrostatic changes of sign from one realm to the other, in equal amounts successively, the most immediate effect is the spreading of the boundary so that it is no longer sharp but assumes a graded transition form.

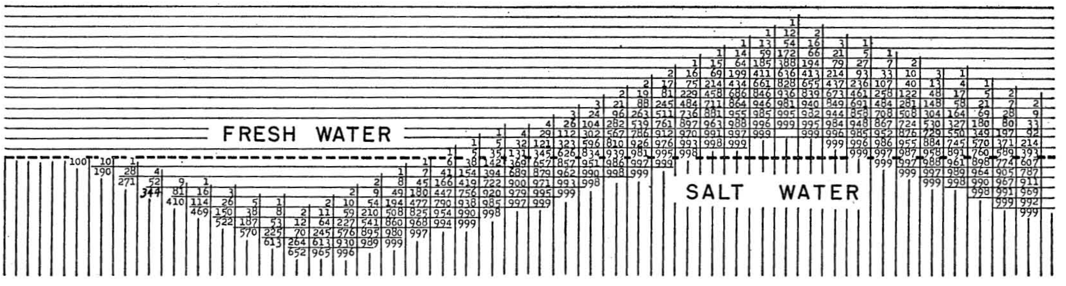

FIG. 3. A numerical model showing growth of the transition zone under the assumption of progressive rinsing, analogous to the exponential theory of rinsing. The unmodified fresh and salt waters are shown by the respective horizontal and vertical hatching. The transition zone is shown by the growing band of figures, the successive values being parts per thousand of salt water.

Figure 3 is a numerical model showing the effect of moving the junction between two types of water to and fro in a permeable medium having some storage capacity. At the beginning of the test period, the junction is assumed to be sharp, as shown by the respective patterns (Fig. 3). Each successive column of figures represents the composition in successive, equal periods of time. The fresh water is assumed to move by 10 successive units of motion against the salt water, thence to retreat by 20 units to a position 10 units on the other, or fresh, side of the initial line of balance, and finally to return by 10 units to that line and thus complete one full cycle. With each unit of movement, the water in a given position is assumed to be made up of 9 parts of oncoming water and 1 part of residual water. It is immaterial for the discussion whether the residue be assumed as 10 per cent or some other figure.

The figures represent parts per thousand of salt water. Above the transition zone all the water is fresh, taken as zero parts. Below it, the water is of sea-water composition, taken as 1,000 parts. A certain raggedness appears at the margins, owing to limiting the calculations to the nearest thousandth. So far as practicable the accumulation of values of the next digit has been anticipated in computing the marginal figures.

It is evident from Figure 3 that changes take place both at the advancing margin and at the following margin. The composition at the advancing margin is changed toward that of the water being invaded, and that change migrates into the advancing front. The same direction of change is reflected through the zone, and the compositions in the following margin also change toward that of the water being invaded. The rates of these changes are determined by the existing gradient of composition at various points in the transition zone.

After the first reversal, the form of the composition diagram becomes nearly symmetrical (Fig. 4). With continued fluctuation the transition zone becomes progressively wider and the rate of change of composition within it is slower. The fresh water is more deeply penetrated by a graded fringe of saline composition and the salt water more deeply penetrated by a graded fringe of freshened water. This effect is indicated in the progressive flattening of the transition curves of Figure 4, as well as by the march of the figures in Figure 3.

It is possible that with a symmetrical series of fluctuations a limit of width would in time be reached in a regularly permeable aquifer. However, in any natural aquifer and particularly with unsymmetrical fluctuations and with movement under new head

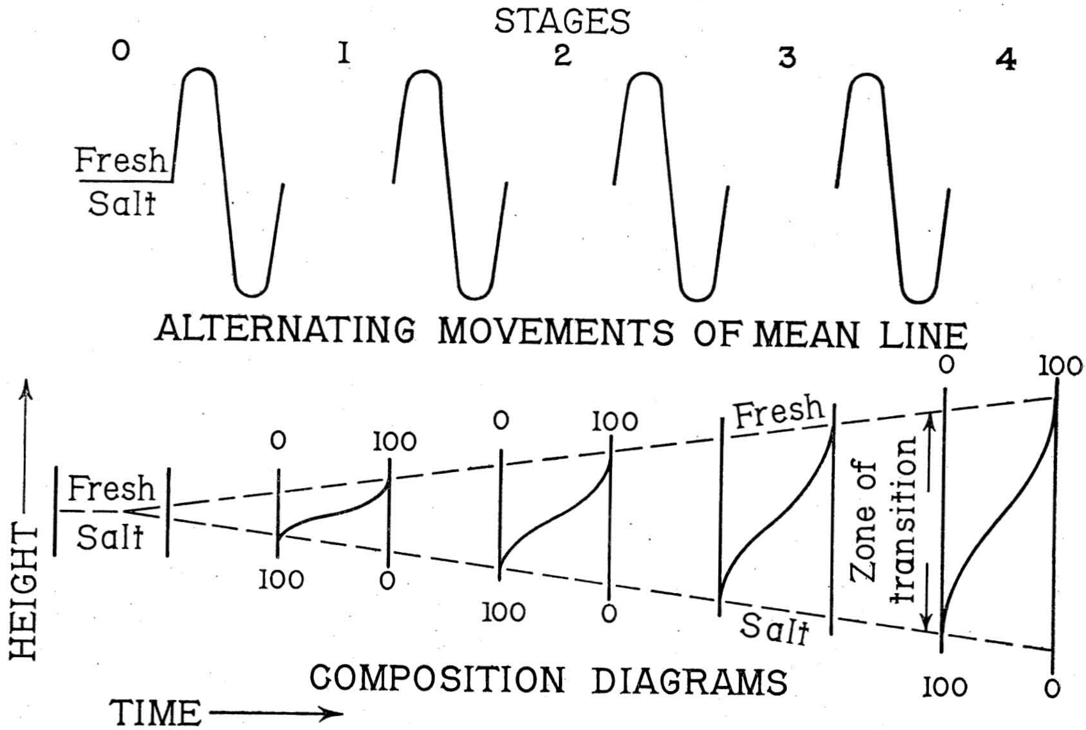

FIG. 4. Schematic diagram showing widening of the transition zone with successive cycles of alternate invasion of one type of water by the other. The lower part shows five composition diagrams, commencing with the sharp boundary at the left. The general sigmoid form of the composition line may be verified by plotting the figures given in the right-hand column of Figure 3.

differences through larger openings in different zones, we cannot doubt that there will be slow and persistent growth in the width of the zone because of this rinsing effect. Thus we suppose that, setting any given limits at the two margins, the thickness of the transition zone will become progressively greater as alternations are repeated, or as the movement assumes greater amplitude.

The composition diagram developed on this assumption of rinsing is a symmetrical curve starting as an asymptote to the zero line of salinity, passing through an inflexion at the 50 per cent point, and terminating as an asymptote to the line of 100 per cent salinity of sea water. After any series of complete cycles the zone has widened, but the line of equivalent density or balance is found in the position formerly occupied by the initial sharp boundary.

REVERSIBILITY

We seem now able to resolve the often discussed problem of reversibility of the process of saline encroachment. This has vexed many people in Hawaii and seems to be clarified by the above discussion. From that line of reasoning, we may say at once that if we consider the position of the 50 per cent line, or the equivalent position of total salt against total fresh water, the process of saline encroachment does appear to be completely reversible. After a period of reversed movement equal in duration and intensity to the earlier saline encroachment, assuming each movement completed, we would expect to find the middle of the zone of transition or diffusion at the same level it occupied initially. However, we are only theoretically interested in the middle of this zone; for practical purposes our interest in an operating Ghyben-Herzberg system is concentrated on that fringe nearest the fresh water, where the salinity is equivalent to the order of 1 per cent of sea water or less. It appears that any movement of the zone of transition causes it to widen. Thus the center of the zone may return to a former position after equal and alternate movements, but the near edge of the zone, judged by any defined standard, because of the previously stated principle of widening will not retract as readily as it advances.

Thus it appears that in the practical sense, in relation to exploitation of potable or agriculturally useful water, the encroachment of saline water, under the natural plus artificial and somewhat aggravated fluctuations, will take place more readily than the reverse process of elimination under a conservation program. Thus there is an element of irreversibility, despite the difficulty which various workers, including the present writer, have had in seeing why the salt water could not be driven back by an equal period of reversed movement. Some have postulated trapping of salt water in pockets. It must, however, be pointed out that in a hydraulic system where water may move either way, trapping is not restricted to pocketing against the direction of gravity but could equally well work the other way with reverse direction of water movement. It is concluded here that no special theory of trapping, especially trapping in one direction, is needed, nor is any theory of directionality required. The condition seems fully explained by the concept of symmetrical thickening, due to rinsing, plus the fixing of practical interest in a position on the near, or upper, side of the zone of transition.

DIFFERENCES IN SYSTEMS

We need now to offer acceptable explanations of the differing qualities of water in various systems. It has been found in various places in Hawaii that the main part of some of the larger Ghyben-Herzberg systems may for many years furnish water of surprising constancy of salinity. There are three most evident sources of sodium chloride: (1) from normal rock weathering, (2) from salts left on the land from salt spray or from more saline irrigation waters, (3) from admixture in the aquifer with intruding sea water.

We are well acquainted with marked increases due to the third factor; there is an equal amount of evidence on aquifers which over a period of many years, and even with considerable reduction of head and increase of draft, continue not to be affected by (3) but represent a stable and not wholly defined combination of (1) and (2). This is true of some aquifers where the draft of water is from points several hundred feet below sea level. Obviously such points are in a part of the Ghyben-Herzberg lens that is not yet affected by saline encroachment (from 3) and cannot be a part of the transition zone. That in course of time, through thickening of the zone, they might become so is, unfortunately, one of the practical lessons we learn.

On the other hand, we find aquifers in which the Ghyben-Herzberg lens at any level, from the top downward, yields water of high salinity, often increasing markedly with draft, and appears to be deriving it from normal and induced admixture of sea water. In such places we can only conclude that the whole lens is a part of the zone of transition. It appears therefore that while some lenses have a considerable fraction of water not affected by the adjacent salt water, others do not. For convenience we may call the upper part the fresh-water core.

MAINTAINING THE CORE

The fresh-water core is a unit through which passes annually the amount of water added to the water table. Some of this water passes down the slope of the water table to escape near the coast, but there is no question that there is considerable deeper circulation. However, except for the migration of the zone of transition with fluctuations of rainfall and draft, and the effect of a few large openings with unbalanced pressures, the water does not move through the transition zone. More properly we can assume that the water in the fresh core circulates past the upper fringe of the transition zone. Presumably this circulation in some lenses is sufficiently active to offer considerable resistance to the thickening of the transition zone. This would operate by rinsing away any slight increases in salinity that might persist if the invading fringe of saline composition were penetrating a truly static body.

It appears that in some of the thicker and more functional Ghyben-Herzberg lenses, the transition zone has not become thick enough to reach the top of the lens. The circulation in this upper fresh-water core is active enough to provide an adequate rinsing action against the upper fringe of the transition zone. Hence the integrity and water quality of the fresh-water core are well maintained. In other lenses, usually much thinner and perhaps developed under less favorable conditions, the transition zone has either thickened to encompass the whole thickness of the lens or perhaps has always had some such thickness. Here there is no fresh-water core, at least not at the coast or where exploration has penetrated.

Experience in finding small amounts of water of low salinity at the very top of such water bodies by no means invalidates the distinctions set forth above. Undoubtedly in wet weather a certain amount of rain water would move down the slope of the water table with only slight mixing with the prevailing ground water; such would be the source of a fresh-water layer, but the layer would be insufficient in amount. Not uncommonly water bodies which will yield fresh water in small samples are found on drilling and pumping to yield only water of considerably higher salinity. For this reason preliminary or bailed samples sometimes lead to hopes that are later not realized.

It is not intended here to treat the various complexities of water development from the Ghyben-Herzberg lens, but the few elements which enter into the problem may be mentioned. We start by emphasizing that the lens is a storage body or gland through which water is moving, and that under balanced conditions the inflow and outflow are equal in amount.

Because the upper surface slopes toward the ocean and the rocks are permeable, there is a steady loss proportional to the head differences through various openings, whose locations are usually not known in detail. So long as this head is maintained these openings, if not plugged, will discharge the same amount of water. If water is to be taken by man, the head must be lowered until the loss from various openings has been reduced by the amount taken artificially. The lowering of head makes water temporarily available from storage at the upper surface; if we follow the Ghyben-Herzberg principle we cannot doubt that in due course the bottom of the lens must shrink to reach a new equilibrium. This will yield, over a long period, very large amounts of water. This condition appears to explain the remarkable stability against draft which is shown by some large systems (Wentworth: 1942).

EFFECT OF DRAFT ON QUALITY

We have seen that the water of the lens is in motion, toward points of outflow, which in hydraulic terms are called sinks. When a well or shaft is dug and water is taken therefrom, this becomes a new point of outflow, or sink. The quality of the water at any given point is determined by the rates and amounts of flow induced under hydraulic conditions from the several accessible sources. Availability of water from those sources depends on the sizes and number of openings connecting them with the sampling point and on the proportionate hydraulic flow induced by draft at the sampling point. When the draft from a well is applied to the pre-existing flow pattern, that pattern is changed and the well competes for water against the other flow lines. The quality of water drawn depends on the flow pattern set up under the new conditions and on the compositions of the several waters available.

The larger the intake surface (as in a long tunnel rather than a small well), the smaller the drawdown required and the smaller the disturbance of pre-existing flow lines required to get the water. In such case the salinity of the water drawn will probably be less modified from that sampled from the aquifer under the original flow conditions. Particularly, the smaller the drawdown, the smaller the likelihood of inducing flow from lower parts of the lens, which may be more saline.

In general, near the coast, the salinity of water taken from a well increases with increase of depth and with increase of draft. It also is greater at low regional heads than at high, and, as stated above, is greater at high drawdown than at low. Two wells of similar depth and location often show quite marked differences, owing to different, though often unknown, openings in the formations they penetrate. Occasionally wells or shafts are dug which encounter openings that are thought to run inland and in which the water becomes less saline as draft is increased; the reverse is far the more common situation. These exceptions do not invalidate any of the recognized principles; they merely emphasize the complexity of the hydrologic conditions involved, and our inability in most cases to make specific predictions.

A Ghyben-Herzberg lens is of great economic value when it has a fresh-water core of such size and stability as to permit the desired draft of fresh water and yet continue to maintain the freshness of the core. Where these conditions of stability exist and can be maintained, the amounts of water which can be taken out and the capacity of the system to sustain short period overdraft are truly astonishing. A great deal of exploration and usually much full-scale operation will be required in most such systems before the safe capacity or other conditions of operation can be determined. The chief requisite in any given case is a body of data that covers a sufficient range of facts and of time, together with recognition of the principles involved. The present paper is offered as an elementary formulation of those principles as they appear at present.

SUMMARY

The Ghyben-Herzberg lens is essentially a gland, into which water moves from rainfall and out of which it moves through natural leaks and artificial discharge. Because of contact with salt water, with which it can mix, the lens of fresh water is in an intermediate condition of equilibrium. To survive, it must not be stagnant; water must move through it. It can be destroyed by too little source water or by too rapid escape of water. In rocks that are too impermeable the dynamic equilibrium may not be set up. The formation and survival of such a lens in a given place depends on the values and mutual relations of the factors of permeability, rainfall, fluctuations in level, regularity of permeability, and presence or absence of a cap rock. Change of one of these conditions, such as fluctuation, may change the balance on which such a lens depends.

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